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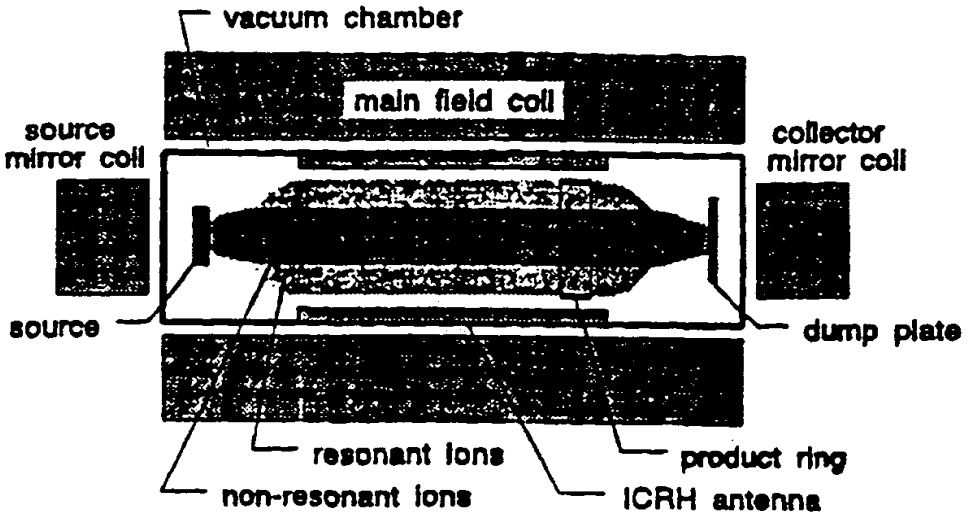

(57) Abstract

Improvements to both the source and collector in a plasma isotope enhancement apparatus are realized in smaller plasma devices without the Calutron processing step. These improvements include the use of a high field source region to generate the plasma, the use of a gas vapor-electron-cyclotron-resonance-heating (gas vapor-ECRH) source, efficient routing of microwave feeds used for the ECRH, replacement of the Calutron process and stabilization of the plasma in a high mirror ratio configuration, computer system control of the entire process for automatic operation, and vertical configuration of the apparatus to allow the use of different types of vapor sources and better use of magnet systems.

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IMPROVEMENTS IN METHOD AND APPARATUS FOR ISOTOPE ENHANCEMENT IN A PLASMA APPARATUS

Background of the Invention

1. Field of the Invention

The invention relates to the field of apparatus and methods for separation of isotopes from each other and in particular to isotopic separations in plasmas.

2. Description of the Prior Art

The invention comprises improvements over the isotopic separation methods and apparatus disclosed by **Dawson**, *"Isotope Separation by Magnetic Fields,"* U.S. Patent 4,081,677 (1978) which is incorporated herein by reference as if set forth in its entirety.

Brief Summary of the Invention

The invention is an improvement in a plasma apparatus for isotope enhancement. The plasma apparatus has an elongated chamber for holding a main plasma. A mechanism generates a predetermined magnetic field in the chamber. A plasma source is provided in the chamber. Another mechanism moves the ionized isotopes from the plasma source along the elongated chamber at a resonance frequency of a desired one of the isotopes. A collector separates the isotopes based on their differential energies. The improvement comprises a pair of magnetic mirrors disposed at opposing ends of the

elongated chamber, so that resonant ions are reflected between the two magnetic mirrors. At least one of the magnetic mirror has a higher field strength than the predetermined magnetic field in the chamber so that nonresonant ions pass through the least one magnetic mirror and resonant ions are reflected therefrom. The collector for the resonant ions comprises a circular ring outside of the main plasma in the elongated chamber.

Similarly the invention is an improvement in a method of providing isotope enhancement in a plasma apparatus described above comprising the steps of reflecting resonant ions between a pair of magnetic mirrors disposed at opposing ends of the elongated chamber, wherein at least one of the magnetic mirror has a higher field strength than the predetermined magnetic field in the chamber so that nonresonant ions pass through the least one magnetic mirror and resonant ions are reflected therefrom. The resonant ions are collected on a circular ring outside of the main plasma in the elongated chamber.

The invention is visualized in the following drawings.

Brief Description of the Drawings

Fig. 1.1 is a schematic of the plasma device.

Fig. 1.2 is a graph of the trajectories of the resonant and nonresonant particles.

Fig. 1.3 is a diagram illustrating in perpendicular cross section taken through the plasma device the radial ion and electron trajectories.

Fig. 1.4 is a graph showing the collision frequencies for slow ions collisions.

Fig. 1.5 is a simplified side view diagram of a collector.

Fig. 2.1 is a graph illustrating the action of the magnetic mirrors.

Fig. 2.2 is a simplified diagram showing the pair of magnetic mirrors and the main elements of the plasma apparatus.

The invention and its various embodiments may now be understood by turning to the following detailed description.

Detailed Description of the Preferred Embodiments

Improvements to the both the source and collector is in a plasma isotope enhancement apparatus are realized in smaller plasma devices without the Calutron processing step. These improvements include the use of a high field source region to generate the plasma, the use of a gas vapor -electron-cyclotron-resonance-heating (gas vapor-ECRH) source. efficient routing of microwave feeds used for the ECRH, replacement of the Calutron process and stabilization of the plasma in a high mirror ratio configuration, computer system control of the entire process for automatic operation, and vertical configuration of the apparatus to allow the use of different types of vapor sources and better use of magnet systems.

Chapter 1

The Plasma Enrichment Process

The plasma enrichment process (PEP) distinguishes between different particle masses by their cyclotron frequency in a magnetic field. Basically, th particles are ionized in near vacuum and placed in a uniform magnetic field, where they orbit, around the field lines, at their cyclotron frequencies. Because of the mass dependence of the cyclotron frequency, particles with a specific mass can be selectively accelerated. This allows discrimination between isotopic masses.

This chapter provides an overview of the plasma enrichment process (PEP) from a theoretical point of view. First a quick overview of a general PEP device is presented, then a historical development of the process, followed by a detailed theoretical analysis of each section of the device. The following chapters discus each section of the Gd-PEP device in greater detail.

1.1 Overview of a PEP device

A PEP device consists of three basic regions (figure 1.1); a source region, an enrichment region, and a collection region (or process). To a large degree, these individual regions can be treated independently, each with its own special requirements.

In a quick overview of a PEP device, the source region produces a plasma that flows into the enrichment region. As the plasma drifts through the en-

richment region, the desired species is selectively heated in the perpendicular direction by ICRH (ion cyclotron resonant heating). Finally, the plasma arrives at the collector region, where particles with "high" perpendicular energy are collected, while particles with "small" perpendicular energy are rejected (collected in a particle dump).

1.2 Units

Unless otherwise stated, all units used in this report will be cgs-gaussian. The only exceptions are for temperatures which are in electron volts and pressures which are in torr.

1.3 Source Region

The source region must produce a plasma from the source material. This plasma should be fully ionized, and have sufficient density to meet the throughput requirements. Additionally, the source must not interfere with the separation process.

Instead of keeping this discussion completely general, it will be assumed that the plasma source is an ECRH (electron cyclotron resonance heating) source. An ECRH source, creates a localized region where the electrons are heated to several eV, by absorption of microwave power at the electron cyclotron frequency. Any neutral particles passing through this region are ionized and confined by the magnetic field, to produce the plasma stream. The ECRH source must be supplied a stream of neutral particles to form the plasma. Currently no restrictions are placed on the neutral source, which could be supplied by direct gas feed, ion sputtering, evaporation, etc. The existence of the ECRH region, however, places several constraints on the system.

To prevent the ECRH source from interfering with the enrichment process, the two regions must be at different magnetic fields. The location of each region is determined by a resonance condition that depends on the magnetic field, this allows the regions to be separated. For clarity, quantities in the source region will be identified with an 'S', and quantities in the enrichment region will be identified with an 'E'. Additionally, it is useful to define

the ratio α of the enrichment magnetic field to the source magnetic field.

$$\alpha = \frac{B_E}{B_S} \tag{1.1}$$

In reality, the magnetic field restrictions on the ECRH region are somewhat stronger. In particular, a particle will gain energy from a wave whenever a harmonic of the particle cyclotron frequency matches the frequency of the wave. For electrons, this can be expressed as:

$$\omega_{ECRH} = \ell\omega_{ce} \tag{1.2}$$

(where ω_{ECRH} is the microwave drive frequency, ℓ is an integer value, and ω_{ce} is the electron cyclotron frequency). From this relation, it can be seen that if the primary ECRH region is created at the magnetic field B_S, there will be additional ECRH regions at, $B_S/2, B_S/3, B_S/4$, and so on. The first harmonic is always the strongest, because the other harmonics couple into the plasma via nonlinear terms. If the plasma passes through any of these other resonant regions, the electrons will be heated, and will again transfer energy to the ions, which is not desireable.[1] Thus to avoid the additional resonant regions, the conditions $\alpha > 0.5$ is imposed.[2]

1.3.1 Plasma Throughput

The major constraint on the source is the particle throughput (Γ). The particle throughput is simply the flow of particles through the device,

$$\Gamma = n_S v_{\parallel S} A_S \xi \tag{1.3}$$

[1]Transferring additional ECRH energy to the plasma will increase the initial temperature of the plasma. This results requiring additional ICRH power to overcome the thermal energy of the plasma (footnote 5). Additionally, the existence multiple resonance regions may prevent propagation of the ECRH power to the actual source location.

[2]In reality the transfer of energy by ECRH is more complicated. In particular, the ECRH can only heat the plasma when the wave has an electric field component parallel to the magnetic field. This additional restriction can be used to provide access for the ECRH source, by routing a waveguide in such a manner that the electric field is always perpendicular to the magnetic field (section ??). In general, however, the condition $\alpha > 0.5$ is practical.

(where n_S is the plasma density, $v_{\parallel S}$ is the parallel velocity, A_S is the plasma area, and ξ is the total efficiency of the system).[3]

An ECRH source produces a density that is determined by the local magnetic field. In particular the ECRH source will produce plasma until cutoff occurs. This is where the electron plasma frequency (ω_{pe}) is equal to the electron cyclotron frequency (ω_{ce}). Thus the source density limit is:

$$\omega_{pe}^2 = \frac{4\pi n_S e^2}{m} \leq \omega_{ce}^2 = \left(\frac{eB_S}{mc}\right)^2 \tag{1.4}$$

(where e is the electron charge, m is the electron mass, and c is the speed of light). This relation can be reduced to

$$n_S \leq \frac{B_S^2}{4\pi m c^2}. \tag{1.5}$$

Examination of the density equation indicates that the plasma density increases as the square of the magnetic field. Thus the highest density, and throughput, are obtained when the source is placed at the highest magnetic field.

The ionized particles leave the ECRH region with a specific temperature, which determines the average parallel drift,

$$v_{\parallel S} = \sqrt{\eta T_{\parallel S}/M} \tag{1.6}$$

(where M is the ion mass, $T_{\parallel S}$ is the parallel plasma temperature in the source region, and $\eta = 1.602 \times 10^{-12}$ erg/eV converts between the energy units eV and erg).

Equations 1.5 and 1.6 can be combined with the flow equation (1.3) to determine the required source area, given the magnetic field and parallel temperature.

$$A_S \geq \frac{4\pi \Gamma c^2 m M_r^{1/2}}{\xi B_S^2 (\eta T_{\parallel S})^{1/2}} \tag{1.7}$$

[3]The total efficiency ξ is the product of the efficiencies of all processes in the device. Most processes have an efficiency of 1. and can be ignored. Some processes, however, have lower efficiencies, and thus degrade the system throughput. The primary processes with efficiencies less than 1 are, plasma production (section ??) and product collection (section 1.5).

From the above analysis it is obvious that the source region is characterized by essentially two numbers, the magnetic field B_S, and the parallel temperature $T_{\parallel S}$. From these numbers all relevant source quantities can be calculated. To fully characterize the plasma parameters (section 1.4), however, the perpendicular temperature in the source region ($T_{\perp S}$) must also be known.

1.4 Enrichment Region

In the enrichment region, the plasma drifts through an ICRH (ion cyclotr n resonant heating) zone. The ICRH drive consists of a rotating electric field that is perpendicular to the main magnetic field (B_E). Because the ICRH coupling is dependent on the magnetic field, the ICRH source must produce a rotating electric field without producing magnetic perturbations along the axis of the device. The desired rotating electric field can be provided by a bifilar antenna [11].

1.4.1 Particle Motions

Considerable insight into the operation of a PEP device can be gained by examining the motion of the plasma in the single particle limit. This model provides only an approximate view of the behavior of plasma in the device, however, it is still adequate to calculate many useful quantities.

Consider a coordinate system where the z-axis lies along the magnetic field. The equations of motion for an ion in the magnetic field are given by,

$$M\dot{v}_x = q\mathcal{E}e^{i\omega_{ICRH}t} + \omega_{ci}v_y \quad (1.8)$$

$$M\dot{v}_y = iq\mathcal{E}e^{i\omega_{ICRH}t} - \omega_{ci}v_x \quad (1.9)$$

(where ω_{ICRH} is the ICRH drive frequency, q is the particle charge, and E is the electric field). These equations can be solved by differentiating each equation and inserting it into the other equation.

$$\dot{v}_x = i(\omega_{ICRH} + \omega_{ci})\mathcal{E}e^{i\omega_{ICRH}t} - \omega_{ci}^2 v_x \quad (1.10)$$

$$\dot{v}_y = -(\omega_{ICRH} + \omega_{ci})\mathcal{E}e^{i\omega_{ICRH}t} - \omega_{ci}^2 v_y \quad (1.11)$$

(Where $\mathcal{E} = qE/M$ is the electric acceleration.)

Figure 1.2: Particle trajectories for resonant and non-resonant particles. The ICRH drive frequency corresponds to a mass unit of 100 (solid line). The dotted lines correspond to non-resonant particles (different masses). The resonant particles continuously gain energy from the ICRH drive. The non-resonant particles first gain energy and then loose energy as they slip out of phase. All particles are started from rest and are followed for a time equal to 75 cyclotron periods for a mass unit 100.

For resonant ions ($\omega_{ci} = \omega_{ICRH}$), these equations have the solution

$$v_x = (\mathcal{E}t + C)e^{i\omega_{ICRH}t} \quad (1.12)$$

$$v_y = i(\mathcal{E}t + C)e^{i\omega_{ICRH}t} \quad (1.13)$$

(where C is a constant determined by the boundary conditions). Resonant ions, thus gain velocity linearly over time (figure 1.2). Non-resonant ions ($\omega_{ci} \neq \omega_{ICRH}$), however, have solutions to equations 1.10 and 1.11 of the form:

$$v_x = \left(\frac{-\mathcal{E}}{(\omega_{ICRH} - \omega_{ci})}e^{i(\omega_{ICRH} - \omega_{ci})t} + C\right)e^{i\omega_{ci}t} \quad (1.14)$$

$$v_y = i\left(\frac{-\mathcal{E}}{(\omega_{ICRH}-\omega_{ci})}e^{i(\omega_{ICRH}-\omega_{ci})t}+C\right)e^{i\omega_{ci}t} \quad (1.15)$$

These particles alternately gain and loose energy in the ICRH region (figure 1.2). The maximum perpendicular velocity gained by a non-resonant particle has the form:

$$\Delta v_{\perp max} = \left|\frac{\mathcal{E}}{\omega_{ICRH}-\omega_{ci}}\right| \quad (1.16)$$

For resonant particles, however, there is no upper bound on velocity gained.

1.4.2 Source Flow

As plasma flows from the source region to the enrichment region, the plasma parameters change. These changes can be understood by knowing that energy, particle flow, and magnetic moment ($Mv_\perp^2/2B$) are conserved as a particle moves from one magnetic field to another [4].

As the particle moves from the source region, both the parallel and perpendicular velocities (and temperatures) are modified. If there is no reflection of the particles (see below), the relation between the source quantities and the enrichment quantities are given by:

$$T_{\perp E} = T_{\perp S}\alpha \quad (1.17)$$
$$v_{\perp E}^2 = v_{\perp S}^2\alpha \quad (1.18)$$
$$T_{\parallel E} = T_{\parallel S} + T_{\perp S}(1-\alpha) \quad (1.19)$$
$$v_{\parallel E}^2 = v_{\parallel S}^2 + v_{\perp S}^2(1-\alpha) \quad (1.20)$$

Examination of the above equations shows that if the particles move from a high field region to a low field region, they gain parallel energy and loose perpendicular energy. In converse, if the particles go from a low field region to a high field region, they gain perpendicular energy and loose parallel energy.

A special case shows up in equation 1.20 when α is very large (travel from a low field region to a high field region). In particular, it is possibl for the right side of this equation to become negative, indicating that the particle could not have made it into this region. This phenomenon is known as magnetic mirroring [1, 5], and will cause particles with insufficient parallel energy (as compared to the perpendicular energy) to be reflected from a high

field region. In general this phenomenon does not present a problem in a PEP device.

Because the plasma particles are essentially "stuck" to the magnetic field lines, the area of the plasma will change, as the magnetic field changes. The change in area is given by

$$A_E = As/\alpha. \tag{1.21}$$

Finally, the plasma density will change. The change plasma density change can be obtained from conservation of particles, which requires that the flow (equation 1.3) is a conserved quantity (if plasma is not being created or destroyed in the region). The change in the plasma density must offset the change in the plasma area (equation 1.21) and the change in the parallel drift velocity (equation 1.20).

$$n_E = \frac{n_s \alpha}{\setminus} \tag{1.22}$$

$$\setminus = \left\{1 + \frac{T_{\perp s}}{T_{\parallel s}}(1-\alpha)\right\}^{\frac{1}{2}} \tag{1.23}$$

1.4.3 Device Length

The length of the enrichment region (L) is determined by the axial drift velocity ($v_{\parallel E}$), and by the mass resolution required. As the device length is increased, the resonant species continues to gain energy and reaches ever increasing orbit size. The non-resonant species, however, are still restricted by equation 1.16 to a maximum velocity.

If the required ratio between the orbit size of the resonant species and the non-resonant species is[4]

$$\mathcal{A} = \frac{r_{Lr}}{r_{Lnr}} \tag{1.24}$$

(where the r_{Lr} and r_{Lnr} are the gyroradii of the resonant and non-resonant species, and the "r" and "nr" indicate resonant and non-resonant, respectively). Expanding the gyroradius in terms of the velocity and cyclotron frequency.

$$\mathcal{A} = \frac{v_{\perp r}}{v_{\perp nr}} \frac{\omega_{cnr}}{\omega_{cr}} \tag{1.25}$$

[4]If there are more then one non-resonant species, then use the species that is closest to the resonant species in mass to determine the device length.

Inserting the velocity gained by resonant particles (equations 1.12 and 1.13), and non-resonant particles (equation 1.16).

$$\mathcal{J} = \frac{\mathcal{E}_r \tau c M_r}{q_r B_E} \frac{B_E q_{nr}}{c M_{nr} \mathcal{E}_{nr}} \left| \frac{q_r B_E}{c M_r} - \frac{q_{nr} B_E}{c M_{nr}} \right| \tag{1.26}$$

$$= \tau \frac{q_r B}{c M_r} \frac{\Delta M}{M_{nr}} \tag{1.27}$$

$$= \tau \omega_{ICRH} \frac{\Delta M}{M_{nr}} \tag{1.28}$$

Where τ is the transit time across the enrichment region and the adjusted mass difference is

$$\Delta M = \left| M_{nr} - M_r \frac{Z_{nr}}{Z_r} \right|. \tag{1.29}$$

In the above derivation, is has been assumed that the initial thermal energy of the particles is small compared to the energy gained from the ICRH drive.[5]

Equation 1.28 can be reversed to determine the required transit time for a particle across the enrichment region.

$$\tau \geq \frac{\mathcal{J}}{\omega_{ICRH}} \frac{M_{nr}}{\Delta M} \tag{1.30}$$

---

[5]The constant C in equations 1.12-1.15 is determined by the boundary conditions on the particle, as it enters the enrichment region. Examination of these equations, indicates that this constant will be on the order of $v_{\perp E}$ (the perpendicular thermal velocity), and can be dropped in the case:

$$\left| \frac{\mathcal{E}}{\omega_{ICRH} - \omega_{cnr}} \right| \gg v_{\perp E}$$

$$\mathcal{E}\tau \gg v_{\perp E}$$

Substituting the perpendicular velocity equation (1.18), and the transit time equation (1.30), these limits can be written as:

$$E \gg \frac{\sqrt{\pi} v_{\perp S} B_E}{c} \frac{Z_r}{Z_{nr}} \frac{\Delta M}{M_r}$$

$$E \gg \frac{\sqrt{\pi} v_{\perp S} B_E}{c \mathcal{J}} \frac{\Delta M}{M_{nr}}$$

Since the value of $\mathcal{J}$ is always above 1, the second restriction can be neglected, and the first equation determines the required field strength.

Combining this with the cyclotron frequency, the number of cyclotron orbits required in the enrichment region is obtained.

$$N = \frac{\beta}{2\pi}\frac{M_{nr}}{\Delta M} \tag{1.31}$$

Alternatively, combining the drift time (equation 1.30) with the parallel drift velocity (equation 1.20), the length of the enrichment region is determined.

$$L = \frac{\beta\chi v_{\parallel S}}{\omega_{ICRH}}\frac{M_{nr}}{\Delta M} \tag{1.32}$$

1.4.4 Plasma Radial Size

The constraints on the area of the plasma column required to get the appropriate throughput (equations 1.7 and 1.21) are not the only area requirements. In particular, if the plasma column is small compared to the gyroradius of the ions, then charge separation can occur (figure 1.3). The electrons have very small gyroradii, and are confined in the center of the column. The ions, however, have larger orbits and thus cover a larger radius. This results in the center of the column becoming negative and the outer edge becoming positive. The resulting radial electric field drives instabilities in the plasma that can disrupt the enrichment process.

To counter this problem, the gyroradius of the accelerated species must be less than the radius of the plasma column. This requirement can be expressed as $\gamma > 1$, where γ is the plasma radius over the accelerated species gyroradius:

$$\gamma = \sqrt{\frac{A_E}{2\pi}}\frac{1}{r_{Lr}} \tag{1.33}$$

If the desired gyroradius of the resonant species is given by R_L, then equations 1.12 and 1.13 can be used to determine the desired electric field strength.

$$E = \frac{R_L B_E \omega_{ICRH}}{eJ}\frac{\Delta M}{M_{nr}} \tag{1.34}$$

Figure 1.3: When the ion gyroradius is large, charge separation can occur. The electrons remain trapped in the center of the column, by their small gyroradius. The ions, however, form a larger cloud around the electrons. This causes the center of the plasma column to become negative, and the surrounding area to become positive. The resultant radial electric field with provides the free energy for plasma instabilities which can disrupt the enrichment process.

Additionally, γ can be written as[6]

$$\gamma = \sqrt{\frac{As}{2\pi a}} \frac{1}{R_L}. \tag{1.35}$$

Solving for the required plasma area.

$$As \geq 2\pi a(\gamma R_L)^2 \tag{1.36}$$

1.4.5 Collisional Considerations

The effect of collisional processes on the plasma in the enrichment region is both important and complex. Initially collisional processes can be divided into collisions effecting the parallel and perpendicular particle motions.

Collisions along the magnetic axis of the device can be neglected. These collisions primarily serve to move all the particles along the device at the same drift speed. At long times, these collisions will begin to convert perpendicular energy (supplied by the ICRH drive) into parallel energy. This would required a slight increase in the device length to get the desired isotopic separation. This process, however, takes a longer time then the typical transit time in the device, thus, does not effect the plasma.

The collisional processes effecting the perpendicular energy of the plasma are more important. Since the mass discrimination is based on selectively increasing the energy of one species over the other, and collisional process that removes energy from the resonant species is important.

Perpendicular collisional processes in the plasma can be divided into four major groups:

1. Collisions at low velocity.

2. Collisions at high velocity.

3. Charge exchange collisions.

[6]An additional form for γ can be obtained by combining equations 1.33 and 1.34.

$$\gamma = \sqrt{\frac{As}{2\pi a}} \frac{\omega_{ICRH}^2}{q_e E A} \frac{\Delta M M_r}{M_{av}}$$

This form of the equation is useful to relate the electric field strength directly to the radius of the plasma column.

4. Collisions between the plasma and neutral particles.

Each of these collisional processes can be examined. To simply the analysis, a very limited collisional model will be used [3]. In particular, the numbers calculated here from collisional effects are only good to an order of magnitude. Whenever possible, however, the errors have been on the conservative side.

Low Velocity Collisions

At low velocity, the plasma collisional process is dominated by long-range coulomb collisions. These collisions essentially provide a viscus drag between the resonant and non-resonant particles (including the electrons). The result of these collisions is to attempt to make all particles move with the same velocity. The collision frequency for slow ions, in the low energy region is [3] (appendix ??):

$$\nu_{is} = 1.6 \times 10^{-9} \frac{n_E Z_r^2 \lambda_{ir}}{\mu_r T_{\perp e}^{3/2}} + \sum_{nr} 6.8 \times 10^{-8} \frac{\sqrt{\mu_{nr}}}{\mu_r} \left(1 + \frac{\mu_{nr}}{\mu_r}\right) \frac{n_{nr} Z_{nr}^2 Z_r^2 \lambda_{ii}}{T_{\perp E}^{3/2}} \tag{1.37}$$

Where μ is the mass number for the ion species, λ is the Coulomb logarithm, and the sum is over all non-resonant ion species. The first term in equation 1.37 is from the slowing of resonant ions from electrons, and the second term comes from slowing due to collisions with non-resonant ions. In the limit of slow plasma collisions, λ is in the range 10–20, and can be approximated by the formulas [3]:

$$\lambda_{ir} \simeq 30 - \ln\left\{\frac{n_r^{1/2} Z_r^3}{\mu_r (eT_{\perp e})^{3/2}}\right\} \tag{1.38}$$

$$\lambda_{ii} \simeq 23 - \ln\left\{\frac{Z_r Z_{nr} (n_r Z_r^2 + n_{nr} Z_{nr}^2)^{1/2}}{\mu_r T_{\perp E}^{3/2}}\right\} \tag{1.39}$$

Where $T_{\perp e}$ is the electron perpendicular temperature at the source, and all ions species are taken to have the same temperature.

Examination of equation 1.37 (figure 1.4) indicates that the collisions rate for ions drops rapidly as the ions gain energy. Because of this rapid drop, a

Figure 1.4: Collisions frequency for slow ion collisions. Although the formula plotted (equation 1.37) becomes increasingly more inaccurate for higher energy ions, it can be seen that as the ion energy increases, the collisions rate decreases. This allows the accelerated ions to runaway to very high energies. The collision frequency is solved using a single non-resonant ion species where $n_r \ll n_{ar}$, $\mu_r \simeq \mu_{ar}$, and $T_{\perp s} = T_{\perp E} = T_\perp$.

thermal runaway condition can be achieved [7, 8]. In this case the resonant species is accelerated sufficiently fast that the collisions rate drops before the energy can be transferred to the non-resonant species.

Because the collision rate increases with the plasma density, the requirement that runaway ions can be created sets an upper limit on the plasma density.

$$\nu_{is} \lesssim \omega_{ICRH} \tag{1.40}$$

This equation can be combined with equation 1.37 to determine the maximum plasma density.

To obtain an expression for the maximum density, some assumptions need to be made. In particular, it will be assumed that there is one major non-resonant ion species that forms the majority of the ions. This gives the following conditions.

$$n_{nr} \simeq n_E \tag{1.41}$$

$$n_e = \zeta n_{nr} \simeq \zeta n_E \tag{1.42}$$

$$n_r \ll n_{nr} \tag{1.43}$$

The ratio of the ion collision frequency to the electron collision frequency can be obtained:

$$\frac{\nu_{is}}{\nu_{es}} = \frac{6.8 \times 10^{-8} \frac{\sqrt{\mu_{nr}}}{\mu_r} \left(1 + \frac{\mu_{nr}}{\mu_r}\right) \frac{n_E Z_{nr}^2 Z_r^2 \lambda_{ii}}{T_{\perp E}^{3/2}}}{1.6 \times 10^{-9} \frac{n_E Z_r^2 \lambda_{ie}}{\mu_r (\alpha T_{\perp e})^{3/2}}} \tag{1.44}$$

$$= 12.5 \frac{\sqrt{\mu_{nr}}(\mu_{nr} + \mu_r) Z_{nr}^2 \lambda_{ii}}{\mu_r \lambda_{ii}} \tag{1.45}$$

$$\gg 1 \tag{1.46}$$

Examination of this ratio indicates, that for slow collisions, only the ion collisions need to be considered. The collision frequency will be simplified by ignoring the density dependence in λ_{ii}. These equations can now be solved for a maximum density.

$$n_E < \frac{1.5 \times 10^7 \omega_{ICRH} \mu_r^2 T_{\perp E}^{3/2}}{\sqrt{\mu_{nr}}(\mu_r + \mu_{nr}) Z_{nr}^2 Z_r^2 \lambda_{ii}} \tag{1.47}$$

High Velocity Collisions

After runaway has occurred, the collisions process is dominated by close-range collisions. These processes include close range Coulomb collisions, charge exchange collisions, and many other processes. In general, these collisions are difficult to accurately calculate, and thus asymptotic formulas for the collisions rates will be used [3]. These formulas are only approximate, thus the results of this calculation are only approximate.

In this region, it is important that adequate time is given to accelerate the resonant species between collisions. This time requirement can be simply stated as [6]

$$\frac{\nu_{ij}}{\omega_{ICRH}} < \frac{\Delta M}{M_r}. \tag{1.48}$$

Using the "slowing-down" collision rate [3]

$$\nu_{ij} \simeq 1.7 \times 10^{-9} \frac{n_E Z_r^2 \lambda_{ir} \sqrt{\mu_r}}{\epsilon^{3/2}} + \sum_{nr} 9.0 \times 10^{-8} \frac{n_{nr} Z_{nr}^2 Z_r^2 \lambda_{ii}}{\sqrt{\mu_r} \epsilon^{3/2}} \left(1 + \frac{\mu_r}{\mu_{nr}}\right) \tag{1.49}$$

(where ϵ is some weighted average energy (in electron volts) for resonant ions in the enrichment region).

Unlike the slow collisions, neither the ion-electron or ion-ion collisions clearly dominate over the other, in this region. Thus both types of collisions must be retained. By making the assumption that there is one dominant non-resonant species ($n_{nr} \ll n_{nr} \simeq n_E$), equation 1.19 can be simplified, and converted into a density limit.

$$n_E < \frac{\Delta M \omega_{ICRH}^{3/2} \mu_{nr} \mu_r^{1/2}}{M_r Z_r^2 \{1.7 \times 10^{-9} \lambda_{ir} \mu_r \mu_{nr} + 9.0 \times 10^{-8} Z_{nr}^2 \lambda_{ii} (\mu_{nr} + \mu_r)\}} \tag{1.50}$$

To finally solve the above equation, some form has to be assumed for the average resonant ion energy ϵ. For simplicity, this energy will be taken to be half the terminal energy of the resonant ions. This gives the following relation.

$$\epsilon = \frac{M_r R_L^2 \omega_{ICRH}^2}{4g} \tag{1.51}$$

The factor η in the denominator is necessary to convert the kinetic energy into electron volts. This can be combined with equation 1.50 to obtain a final form for the density limit.

$$n_E < \frac{\Delta M M_r^{1/2} R_L^3 \omega_{ICRH}^4 \mu_{nr} \mu_r^{1/2}}{S\eta^{3/2} Z_r^2 \{1.7 \times 10^{-9} \lambda_{ii} \mu_r \mu_{nr} + 9.0 \times 10^{-8} Z_{nr}^2 \lambda_{ii} (\mu_{nr} + \mu_r)\}} \quad (1.52)$$

Charge exchange collisions

Another collisional process that becomes dominate at very high energies is charge exchange. In this process, an accelerated (resonant) ion exchanges an electron with either a neutral particle or with a multiply charged atom. This is significant because such interactions destroy the resonance condition for the ion. In either interaction, the charge state of the resonant ion is changed and the resultant particle is no longer resonant.

Charge exchange with neutral ions can be reduced to a non-significant level by controlling the concentration of neutrals (see next section). Charge exchange between different changed states of the resonant ions can be prevented by allowing only a single charge state in the system. In most cases the base charge state will be the used ($Z_r = Z_{nr} = 1$). By preventing production of any other charged states (section ??) this process can be reduced to an insignificant level.

Additionally, the charge exchange cross section is strongly dependent on the velocity of the ions. This allows additional control of the process by keeping the particle velocities to a moderate level. Target resonant ions in the Gd-PEP device will have a 20-30 eV energies, and thus are relatively slow for charge exchange. Additional study of the charge exchange process will be required before final construction of a Gd-PEP device, however, given the low number of neutral and/or doubly ionized particles in the Gd-PEP device, charge exchange does not appear to present a problem.

Neutral-Plasma Collisions

Collisions between neutral particles and the plasma present a much smaller problem. This is mostly because the uncharged neutral particles cannot interact with ions at long range. Instead, these collisions are very short range, and thus have smaller cross sections. Further, neutral collisions can be easily

controlled by simply removing the neutrals. In general, the assumption will be made that

$$n_n \ll n_E \tag{1.53}$$

(where n_n is the neutral density). This condition guarantees that plasma collisions dominate over neutral collisions. Combining the above equation with the ideal gas law, the maximum neutral pressure in the system can be obtained.[7]

$$p \ll 3.11 \times 10^{-17} n_E \tag{1.54}$$

1.5 Collection Process

The collection process is the final stage of the device. Here, particles with "high" perpendicular energy are collected as product and particles with "low" perpendicular energy are rejected (collected as tailings). Only the simplest form of collector is described here. A more advanced collector system is currently being developed at UCLA (chapter 2). If this collector is successful, it will allow for very high enrichments ($\sim 99\%$), and very high collector efficiencies ($\simeq 1$). This advanced collector design, however, requires a B type PEP device (section 1.6).

The simplest collector design (figure 1.5) consists of a series of slats and plate parallel and perpendicular to the magnetic field. "Shield-slats" are perpendicular to the field, "product plates" are parallel to the field, and finally, a "dump plate" is perpendicular to the field. Particles enter the collector region between the shield-slats and are either collected on the product plates or the dump plate.

When non-resonant particles enter the collection region, these particles have small gyroradii and thus cannot be collected on the product plates. In-

[7] The ideal gas law

$$pV_m = RT$$

(where p is the pressure, V_m is the volume occupied by a mole of gas, $R = 8.31 \times 10^7$ erg/mol/K is the molar gas constant, and T is the gas temperature (in Kelvin)). This expression is solved for V_m, which is the volume containing $N_A = 6.02 \times 10^{23}$ par/mol particles. Solving for the pressure from the neutral density,

$$p = 3.11 \times 10^{-17} n_n$$

Figure 1.5: Simple collector design. Particles that pass the shield-slats and enter the collector region are either collected on the product or dump plates. Resonant particles, have large gyroradii, and are collected on the product plates. Non-resonant particles, have small gyroradii, and pass through the collector region and are collected on the dump plates. Some particles strike the shield-slats and are not selectively collected by the system.

stead, these particles travel through the collection region and are collected on the dump plate. Resonant particles, however, have sufficiently large gyroradii that they are collected on the product plate, and do not reach the dump plate.

The major problem with this collector system is that particles striking the shield-slats are completely lost to the system. The optimal settings of the product plates and the height of shield plates determines the collector efficiency. To guarantee collection of all product material, adjacent product plates should be placed at distance $2R_L$. To eliminate all non-resonant ions, the shield-slats must be $2R_L/\mathcal{A}$ wide. This leads to the collector efficiency (fraction of product material collected) of

$$\xi_c = \frac{\mathcal{A}-1}{\mathcal{A}}. \tag{1.55}$$

1.6 Type A and Type B Devices

PEP devices can be divided into two basic types, A and B. The type A machine, is the now classical design that was developed at TRW [11]. The source is placed in a low field region, and the enrichment is performed in a high field region ($\alpha > 1$). The A type device has two major advantages:

1. These devices have been constructed and shown to operate [6, 11].

2. The higher magnetic field in the enrichment region will result in a physically smaller device.

The second design is the type B machine. These devices place the source in a high field and perform the enrichment in a low field region ($\alpha < 1$). These devices have several advantages:

1. The higher magnetic field at the source allows production of a higher density plasma (equation 1.5), making it easier to generate the required throughput.

2. As the plasma expands into the low field region, the perpendicular plasma temperature drops (equation 1.18), this allows a smaller ICRH drive amplitude to overcome the thermal energy in the plasma.

parameter	formula	description
B_S	--	source magnetic field
B_E	--	enrichment magnetic field
$T_{\perp S}$	--	perpendicular source temperature
$T_{\parallel S}$	--	parallel source temperature
β	r_{Lr}/r_{Lnr}	resonant to non-resonant gyroradius ratio
γ	r_p/R_L	plasma to resonant ion radius radio
ζ	n_r/n_{nr}	resonant to non-resonant density radio
R_L		gyroradius of resonant ion at collector
μ_r		mass number for resonant ions
μ_{nr}		mass number for non-resonant ions
Z_r		charge state for resonant ions
Z_{nr}		charge state for non-resonant ions
Γ	--	required particle throughput

Table 1.1: This table summarizes the parameters that must be known to design a PEP device.

3. The existence of the high field region on the end of the device allows a more advanced collector to be used (section 1.5).

4. Reduced cost for generation of magnetic field.

1.7 Summary

This section contains a summary of the equations that govern the design of a PEP device. The parameters that must be known to use these equations are defined in table 1.1.

General quantities:

$$\alpha = \frac{B_E}{B_S} \tag{1.56}$$

$$\Delta\mu = \mu_{nr} - \frac{Z_{nr}}{Z_r}\mu_r \tag{1.57}$$

$$\lambda = \left\{1 + \frac{T_{\perp s}}{T_{\parallel s}}(1-\alpha)\right\}^{\frac{1}{2}} \tag{1.58}$$

Conditions required by the source region (sections 1.3 and 1.3.1):

$$\alpha > 0.5 \tag{1.59}$$

$$n_s \leq \frac{B_z^2}{4\pi m c^2} \tag{1.60}$$

$$A_s \geq \frac{4\pi^2 c^2 m (M_p \mu_r)^{1/2}}{\xi B_z^2 (\eta T_{\parallel s})^{1/2}} \tag{1.61}$$

$$f_{ECRH} = \frac{e B_z}{2\pi m c} \tag{1.62}$$

Enrichment region changes (section 1.1.2):

$$A_E = \frac{A_s}{\alpha} \tag{1.63}$$

$$n_E = \frac{n_s \alpha}{\lambda} \tag{1.64}$$

$$f_{ICRH} = \frac{Z_c e B_E}{2\pi M_p \mu_r c} \tag{1.65}$$

Mass resolution and size requirements (sections 1.4.3 and 1.4.4):

$$\tau \geq \frac{3 M_p \mu_r \mu_{ar} c}{Z_c e B_E \Delta\mu} \tag{1.66}$$

$$L \geq \frac{\sqrt{3} v_{ci} \mu_{ar} (M_p \mu_r \eta T_{\parallel s})^{1/2}}{Z_c e B_E \Delta\mu} \tag{1.67}$$

$$E \geq \frac{R_L Z_c e B_E^2 \Delta\mu}{c^2 M_p \mu_r \mu_{ar}} \tag{1.68}$$

$$A_s \geq 2\pi\alpha(\gamma R_L)^2 \tag{1.69}$$

Collisional considerations (section 1.1.5):

$$\Lambda_{ie} \simeq 30 - \ln\left\{\frac{Z_r^2 (\zeta n_s)^{1/2}}{\lambda^{1/2} \mu_r \alpha T_{\perp e}^{3/2}}\right\} \tag{1.70}$$

$$\Lambda_{ii} \simeq 23 - \ln\left\{\frac{Z_r Z_{ar}^2 n_s^{1/2}}{\lambda^{1/2} \mu_r \alpha T_{\perp s}^{3/2}}\right\} \tag{1.71}$$

$$n_S < \frac{1.5 \times 10^7 \gamma e B_E \mu_r \alpha^{1/2} T_{\perp S}^{3/2}}{c M_\mu \mu_{nr}^{1/2} (\mu_r + \mu_{nr}) Z_{nr}^2 Z_r \lambda_{ii}} \quad (1.72)$$

$$n_S < \frac{\Delta\mu \mu_{nr} R_L^3 Z_r^2 e^4 B_E^4 \lambda}{8\eta^{3/2} M_p^{5/2} \mu_r^3 e^4 \alpha} \times \left\{ \frac{1}{1.7 \times 10^{-9} \lambda_{ii} \mu_r \mu_{nr} + 9.0 \times 10^{-8} Z_{nr}^2 \lambda_{ii} (\mu_{nr} + \mu_r)} \right\} \quad (1.73)$$

1.7.1 Numerical Forms

The above equations can be converted into a numerical form for quick calculations:

Source:

$$n_S \leq 9.71 \times 10^4 B_S^2 \quad (1.74)$$

$$\lambda_S \geq 1.05 \times 10^{-11} \frac{\Gamma \mu_r^{1/2}}{\xi B_S^2 T_{\perp S}^{1/2}} \quad (1.75)$$

$$f_{\text{ECRH}} = 2.80 \times 10^6 B_S \quad (1.76)$$

Enrichment/Flow:

$$\lambda_E = 1.05 \times 10^{-11} \frac{\Gamma \mu_r^{1/2}}{\xi \alpha B_S^2 T_{\perp S}^{1/2}} \quad (1.77)$$

$$n_E = 9.71 \times 10^4 \frac{\alpha B_S^2}{\lambda} \quad (1.78)$$

$$f_{\text{ECRH}} = 1.52 \times 10^4 \frac{Z_r B_E}{\mu_r} \quad (1.79)$$

Resolution:

$$\tau \geq 1.01 \times 10^{-4} \frac{3\mu_r \mu_{nr}}{Z_r B_E \Delta\mu} \quad (1.80)$$

$$L \geq 102 \frac{\lambda 3\mu_{nr} (\mu_r T_{\parallel S})^{1/2}}{Z_r B_E \Delta\mu} \quad (1.81)$$

$$E \geq 3.19 \times 10^{-5} \frac{R_L Z_r^2 B_E^2 \Delta\mu}{3\mu_r \mu_{nr}} \quad (1.82)$$

$$\lambda_S \geq 2\pi\alpha(\gamma R_L)^2 \quad (1.83)$$

Collisional:

$$\lambda_{ir} \simeq 30 - \ln\left\{312\frac{Z_r^2 C^{1/2} B_S}{\lambda^{1/2}\mu_r a T_{\perp e}^{3/2}}\right\} \quad (1.84)$$

$$\lambda_{ii} \simeq 23 - \ln\left\{312\frac{Z_r Z_{nr}^2 B_S}{\lambda^{1/2}\mu_r a T_{\perp S}^{3/2}}\right\} \quad (1.85)$$

$$n_S < 1.11 \times 10^{11}\frac{\lambda B_E \mu_r a^{1/2} T_{\perp S}^{3/2}}{\mu_{nr}^{1/2}(\mu_r + \mu_{nr}) Z_{nr}^2 Z_r \lambda_{ii}} \quad (1.86)$$

$$n_S < \frac{1.12 \times 10^{-3}\Delta\mu\mu_{nr} R_L^3 Z_r^2 B_E^4 \lambda}{a\mu_r^2\{1.7 \times 10^{-3}\lambda_{ir}\mu_r\mu_{nr} + 9.0 \times 10^{-8} Z_{nr}^2 \lambda_{ii}(\mu_{nr} + \mu_r)\}} \quad (1.87)$$

1.7.2 The Gd-PEP Device

Considering a device to enrich ${}_{64}Gd^{157}$ from ${}_{64}Gd^{156}$, the above formulas can be simplified further. Since discrimination between ${}_{64}Gd^{157}$ and ${}_{64}Gd^{156}$ will be more demanding then discrimination between ${}_{64}Gd^{157}$ and any other Gd isotope, this simplification can be made. In particular the following numbers can be specified:

$$\mu_r = 157 \quad (1.88)$$

$$\mu_{nr} = 156 \quad (1.89)$$

$$Z_r = 1 \quad (1.90)$$

$$Z_{nr} = 1 \quad (1.91)$$

$$\Gamma = 5.15 \times 10^{20}\ \text{particles/s} \quad (1.92)$$

$$C = 0.157\ {}_{64}Gd^{157}\ \text{per}\ {}_{64}Gd^{156} \quad (1.93)$$

Additionally, it will be assumed that the ECRH plasma source produces an isotropic plasma [9]. Thus $T_{\perp S} = T_{\parallel S} = T_S$, and $\Delta\mu = 1$. Combining these numbers with the above formulas, a set of formulas specifically for a Gd-PEP device can be obtained.

General:

$$a = \frac{B_E}{B_S} \quad (1.94)$$

$$\lambda = \sqrt{2 - a} \quad (1.95)$$

Source:

$$n_S \leq 9.71 \times 10^{4} B_S^2 \quad (1.96)$$

$$\lambda_S \geq \frac{7.17 \times 10^{10}}{\sqrt{B_S^4 T_S^{1/2}}} \quad (1.97)$$

$$f_{ECRH} = 2.80 \times 10^{6} B_S \quad (1.98)$$

Enrichment/Flow:

$$\lambda_E = \frac{7.17 \times 10^{10}}{\xi \alpha B_S^4 T_{\perp S}^{1/2}} \quad (1.99)$$

$$n_E = 9.71 \times 10^{4} \frac{\alpha B_S^2}{\lambda} \quad (1.100)$$

$$f_{ECRH} = 9.68 B_E \quad (1.101)$$

Resolution:

$$\tau \geq 2.55 \frac{A}{B_E} \quad (1.102)$$

$$L \geq 1.99 \times 10^{5} \frac{\sqrt{A} T_S^{1/2}}{B_E} \quad (1.103)$$

$$E \geq 1.30 \times 10^{-11} \frac{R_L B_E^2}{A} \quad (1.104)$$

$$\lambda_S \geq 2\pi \alpha (\gamma R_L)^2 \quad (1.105)$$

Collisional:

$$\lambda_{ii} \simeq 30 - \ln \left\{ 0.787 \frac{B_S}{\sqrt{\lambda^{1/2} \alpha T_{\perp e}^{3/2}}} \right\} \quad (1.106)$$

$$\lambda_{ii} \simeq 23 - \ln \left\{ 1.99 \frac{B_S}{\sqrt{\lambda^{1/2} \alpha T_S^{3/2}}} \right\} \quad (1.107)$$

$$n_S < 5.78 \times 10^{9} \frac{\sqrt{B_E} \alpha^{1/2} T_S^{3/2}}{\lambda_{ii}} \quad (1.108)$$

$$n_S < 0.175 \frac{R_L^2 B_E^4 \sqrt{\lambda}}{\alpha (162 \lambda_{ii} + 109 \lambda_{ii})} \quad (1.109)$$

Chapter 2

Advanced Collector

A major improvement can be made to the PEP system by changing the collector. The collector system described in section 1.5 has the advantages of being both simple and previously tested [11]. This collector, however, has several disadvantages. In particular, geometric considerations limit the collector efficiency to $\xi_c = (A-1)/A$. Plasma considerations, limit the purity of both the product and tailing produced by this system.

Using global properties of the plasma, it is possible to design a collector system that should allow essentially 100% recovery of both product and tailing material. In effect, this system produces two outputs, a product collector that contains 100% product, and a dump plate that contains only non-product material.

This new collector design is referred to, in this report, as the "advanced collector." A full description of this collector system requires complexities of plasma physics which are beyond the scope of this report. The basic idea, however, can be explained fairly simply.

To understand the collector system, the concept of a magnetic mirror (first introduced in section 1.1.2) must be understood. This phenomenon occurs when plasma particles travel from a low field region to a high field region. Here, both the particle energy and the magnetic moment of the particles are conserved. Conservation of magnetic moment requires that as a particle enters the high field region it's perpendicular velocity increases. Combined with conservation of energy this implies that the axial velocity of the particle decreases. If the increase in the field is sufficiently large the particle will stop and be reflected.

Figure 2.1: Particles confined by a magnetic mirror. The dashed line shows the boundary between particles confined and not confined by a magnetic mirror. The slope of the diagonal line is $(B_2/B_1 - 1)$, and B_2/B_1 is referred to as the mirror ratio. The conical area of particles not reflected from the mirror is referred to as the loss-cone.

The axial velocity of a particle entering a high field region is given by (see derivation of equation 1.20)

$$v_{\parallel 2}^2 = v_{\parallel 1}^2 + v_{\perp 1}^2 \left(1 - \frac{B_2}{B_1}\right) \tag{2.1}$$

(where B_1 is the low magnetic field and B_2 is the high magnetic field). Examination of this equation indicates that if the mirror ratio (B_2/B_1) is fixed, particles with sufficiently high $v_\perp$ (relative to $v_\parallel$) will be reflected from the mirror, but particles with low perpendicular velocity will pass through the mirror (figure 2.1).

In the enrichment region of a PEP device, the perpendicular velocity of the resonant ions is greatly increased, while the parallel velocity remains unchanged. Consider a PEP device with magnetic mirrors on both sides of the device (figure 2.2). This necessitates a type B device (section 1.6). By careful choice of the mirror ratio on the collector side of the device, the resonant particles which have a much higher perpendicular velocity can be reflected from the mirror. The non-resonant particles, however will travel directly through the mirror onto the dump plate.

Figure 2.2: Shown is the advanced collector system. The system operates by generating magnetic mirrors on both sides of the enrichment region. The source is located in one mirror, and a dump plate is located beyond the other mirror (collector mirror). The collector mirror is adjusted such that non-resonant particles are not reflected by this mirror, but the accelerated resonant particles are. Thus the non-resonant particles make one transit across the device and are collected on the dump plate. The resonant particles are trapped between the two mirrors, and diffuse out radially until they are collected on the product ring.

The discrimination at the end mirror can be adjusted to be very good. This can be done because the average resonant particle has β^2 times the energy of the average non-resonant particle.

At this point, the majority of the non-resonant particles have left the device on the first transit across the device. The resonant particles, however, are reflected from the collector side and travel backward through the enrichment region. Here some particles will be decelerated, and some particles will be accelerated by the ICRH field, depending on the phase at which the particles enter the field. In either case, particles reaching the source region will either be reflected there, or absorbed back onto the cathode.

In actuality, most resonant ions will be reflected at the source region mirror. This is for several reasons:

1. Extremely few particles will enter the enrichment region exactly 180° degrees out of phase with the ICRH drive and lose sufficient energy to pass though the source region mirror.

2. The source region mirror ratio can be adjusted to be higher then the collector side mirror. This will greatly increase the number of reflected ions.

3. Finally, the helical nature of the ICRH drive field will tend to prevent loss of all gained perpendicular energy during the backward transit of the enrichment region.

The majority of the resonant ions become trapped between the source region mirror and the collector region mirror. The non-resonant ions, however, will simply pass through both mirrors and be collected on the dump plate.

The resonant ions are not trapped by the mirrors forever. Plasma effects [5] and the effective scattering from the enrichment region[1] will cause radial transport in the resonant ions. These ions can then be collected on a circular ring outside the radius of the main plasma.

As was stated earlier, a complete discussion of the proposed advanced collector system is beyond the scope of this report. The following sections

[1]As a resonant ion passes back and forth through the enrichment region, it will encounter the ICRH drive field at random phase. This will form a scattering source that will cause a radial random walk in the guiding center for the ion.

contain comments on some of the important topics relating to this new collector and device configuration. A full investigation of the collector system using more advanced theoretical models, computer simulations, and experimental exploration is required.

2.1 Instabilities

Magnetic mirrors were first developed as a possible fusion devices. Instabilities that scattered particles into the mirror loss-cone eventually put an end to this line of development. Loss-cone scattering is essentially velocity space scattering of particles. This was significant in the fusion program, because particles scatted into the loss-code were not confined by the magnetic mirrors and thus were not confined by the device. These instabilities are driven by the hole in the particle distribution caused by removal of all particles in the loss-cone.

Loss-cone instabilities should not effect the PEP device, for several reasons. First, the loss-cones are not empty, but rather full of particles. These particles are, however, not confined within the device, but simply passing through. Second, in the case of the Gd-PEP device, only the resonant particles are confined by the mirror. These particles are such a small fraction of the total number of particles, that instabilities should not be a problem.

2.2 Neutral Control

The simple collector was immune to neutral particles produced by the source. This is because neutral particles essentially move with line-of-sight motion, and the product plates are protected by the shield-slats (section 1.5).

In the advanced collector system, the product ring may be in line-of-sight from the source. This problem can be controlled by:

1. Controlling the production of neutrals (section ??).
2. Angling the product ring such that it presents a small solid angle to the source.
3. Placing the product ring such that it is not in line-of-sight from the source.

2.3 Column Area and Collisions

Because the advanced collector system relies on radial transport properties of the plasma, it will be less sensitive to several effects. First, charge separation effects from ions outside the plasma column are minimized. This is because some of the plasma electrons are also confined by the mirror, and thus radially diffuse with the resonant ions (providing for neutralization).

Collisions with plasma particles can be tolerated to a higher degree. This is because the mean time between collisions does not have to be the entire acceleration time for the resonant ion, but simply sufficient time to accelerate to the point where the ion is trapped by the magnetic mirrors.

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Many alterations and modifications may be made by those having ordinary skill in the art without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiment has been set forth only for the purposes of example and that it should not be taken as limiting the invention as defined by the following claims.

The words used in this specification to describe the invention and its various embodiments are to be understood not only in the sense of their commonly defined meanings, but to include by special definition in this specification structure, material or acts beyond the scope of the commonly defined meanings. Thus if an element can be understood in the context of this specification as including more than one meaning, then its use in a claim must be understood as being generic to all possible meanings supported by the specification and by the word itself.

The definitions of the words or elements of the following claims are, therefore, defined in this specification to include not only the combination of elements which are literally set forth, but all equivalent structure, material or acts for performing substantially the same function in substantially the same way to obtain substantially the same result.

Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

The claims are thus to be understood to include what is specifically illustrated and described above, what is conceptionally equivalent, what can be obviously substituted and also what essentially incorporates the essential idea of the invention.

We claim:

1. An improvement in a plasma apparatus for isotope enhancement, said plasma apparatus having an elongated chamber for holding a main plasma, means for generating a predetermined magnetic field in said chamber, a plasma source in said chamber, means for moving ionized isotopes from said plasma source along said elongated chamber at a resonance frequency of a desired one of said isotopes, and a collector for separating said isotopes based on their differential energies, said improvement comprising:

a pair of magnetic mirrors disposed at opposing ends of said elongated chamber, so that resonant ions are reflected between said two magnetic mirrors, wherein at least one of said magnetic mirror has a higher field strength than said predetermined magnetic field in said chamber so that nonresonant ions pass through said least one magnetic mirror and resonant ions are reflected therefrom, said collector for said resonant ions comprising a circular ring outside of said main plasma in said elongated chamber.

2. An improvement in a method of providing isotope enhancement in a plasma apparatus, said plasma apparatus having an elongated chamber for holding a main plasma, means for generating a predetermined magnetic field in said chamber, a plasma source in said chamber, means for moving ionized isotopes from said plasma source along said elongated chamber at a resonance frequency of a desired one of said isotopes, and a collector for separating said isotopes based on their differential energies, said improvement comprising the steps of:

reflecting resonant ions between a pair of magnetic mirrors disposed at opposing ends of said elongated chamber, wherein at least one of said magnetic mirror has a higher field strength than said predetermined magnetic field in said chamber so that nonresonant ions pass through said least one magnetic mirror and resonant ions are reflected therefrom; and

collecting said resonant ions on a circular ring outside of said main plasma in said elongated chamber.

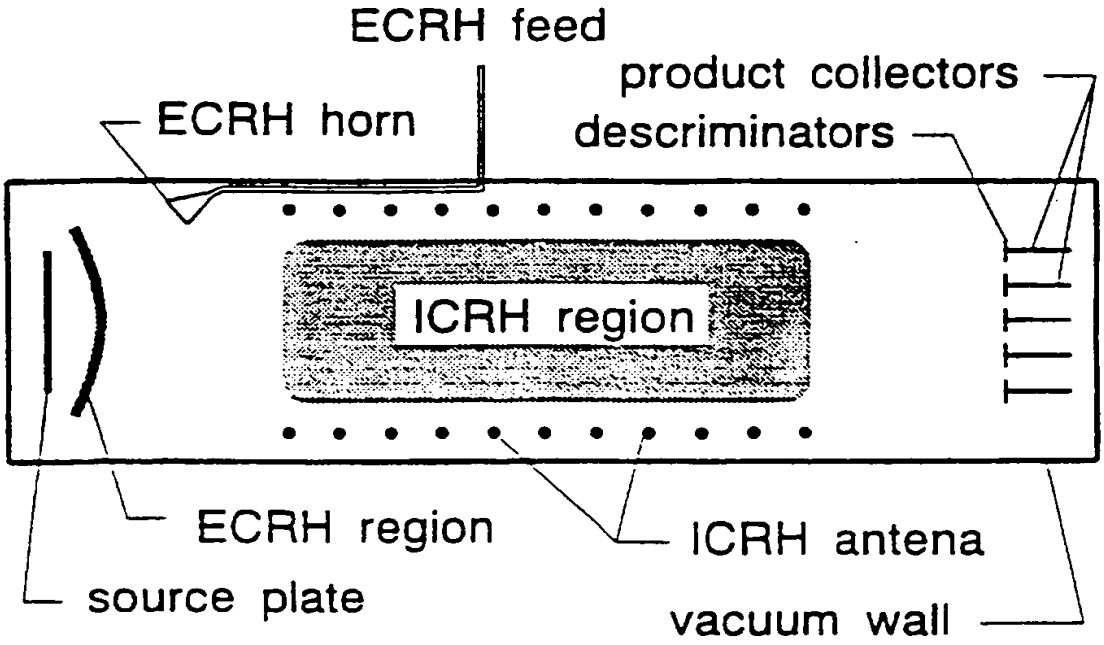

Figure 1.1: Schematic overview of a PEP device.

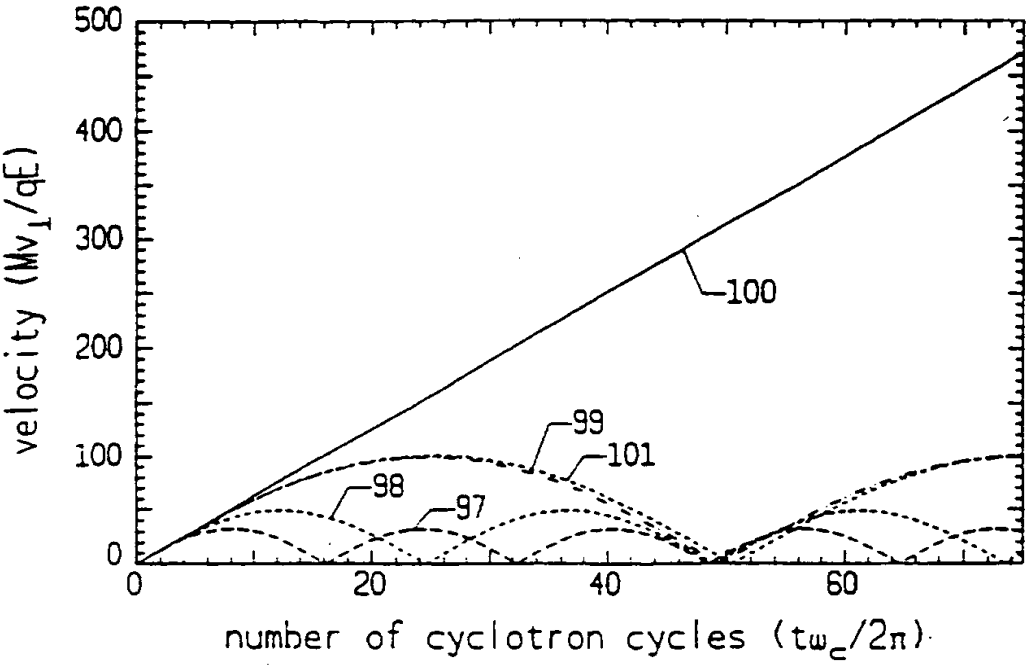
500
400
300
200
100
0
velocity ($Mv_\perp/qE$)
0
20
40
60
number of cyclotron cycles ($t\omega_c/2\pi$)
100
99
101
98
97

Fig. 1.2

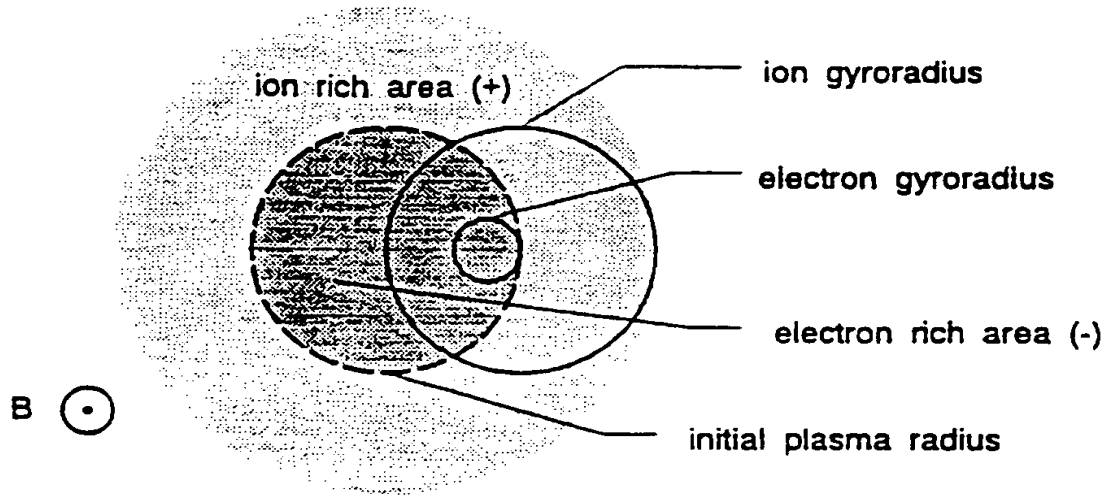
ion rich area (+)
ion gyroradius
electron gyroradius
electron rich area (-)
B
initial plasma radius

Fig. 1.3

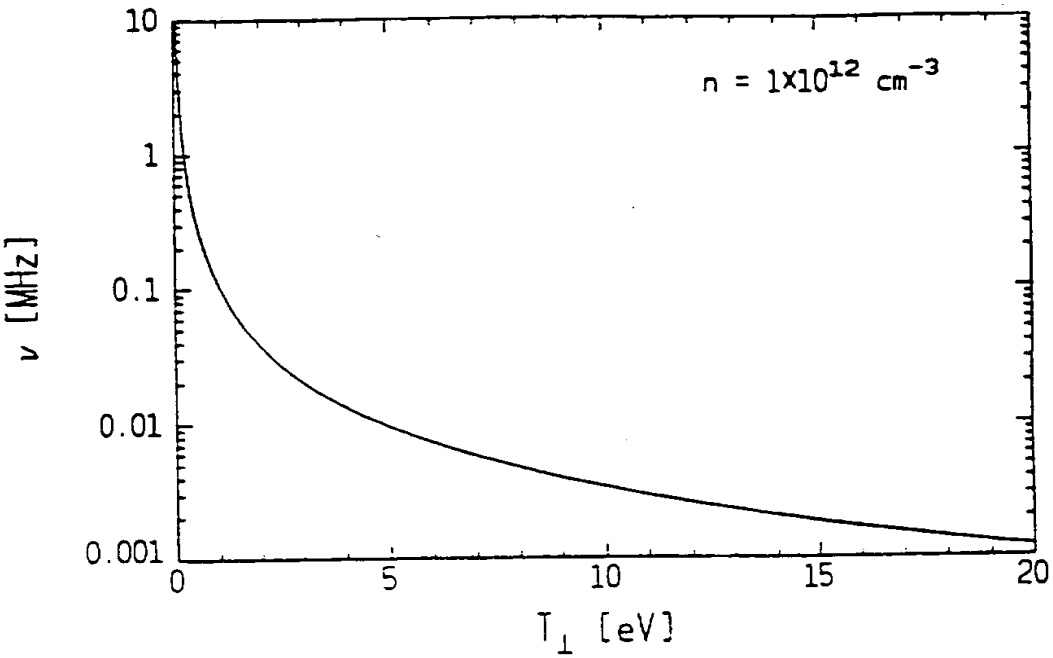

Fig. 1.4

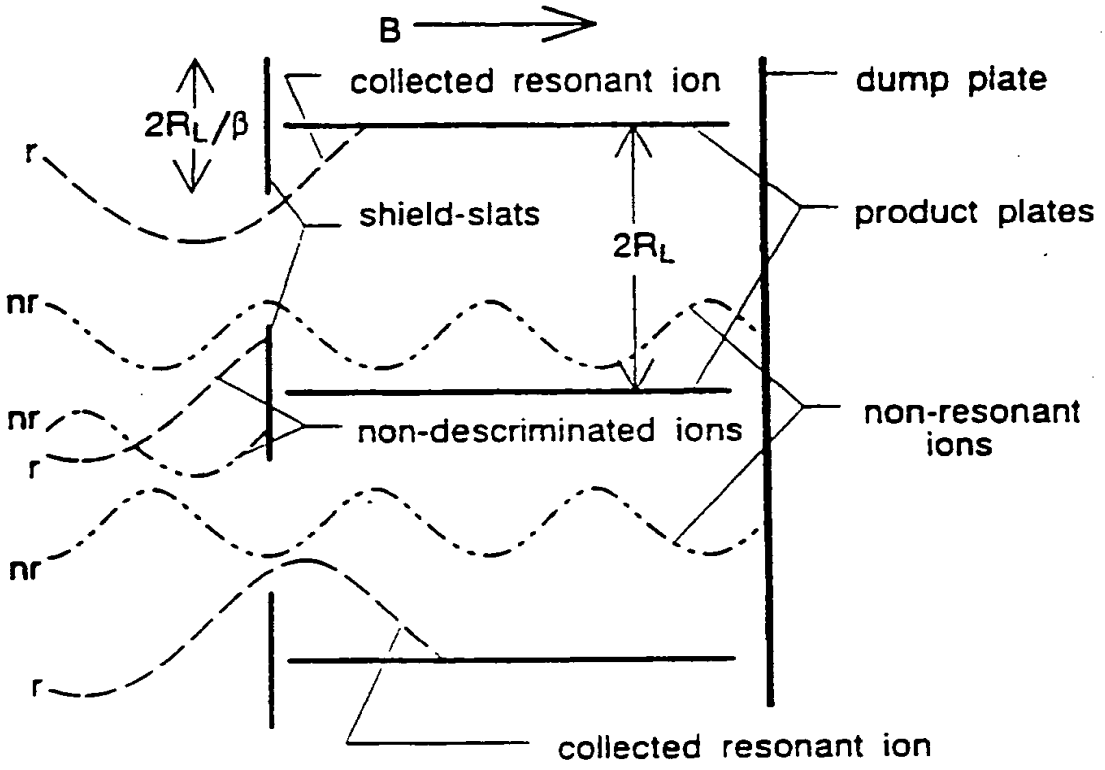
B
collected resonant ion
dump plate
$2R_L/\beta$
r
shield-slats
product plates
$2R_L$
nr
nr
non-descriminated ions
non-resonant ions
r
nr
r
collected resonant ion

Fig. 1.5

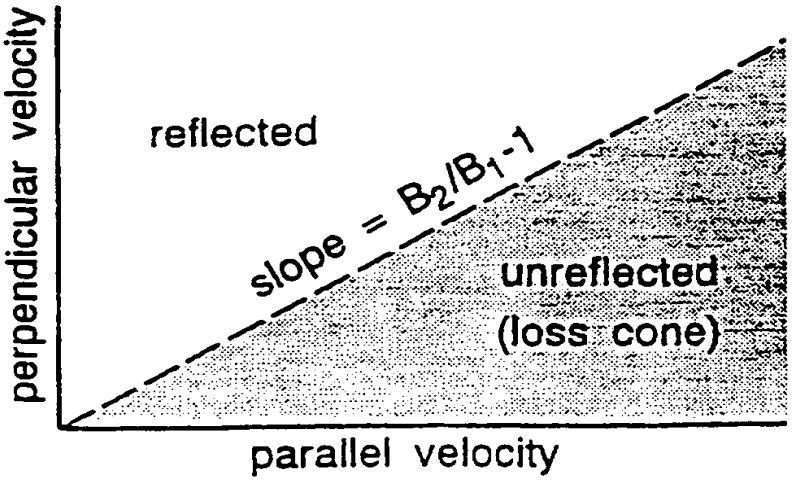
perpendicular velocity
reflected
slope = B_2/B_1-1
unreflected
(loss cone)
parallel velocity

Fig. 2.1

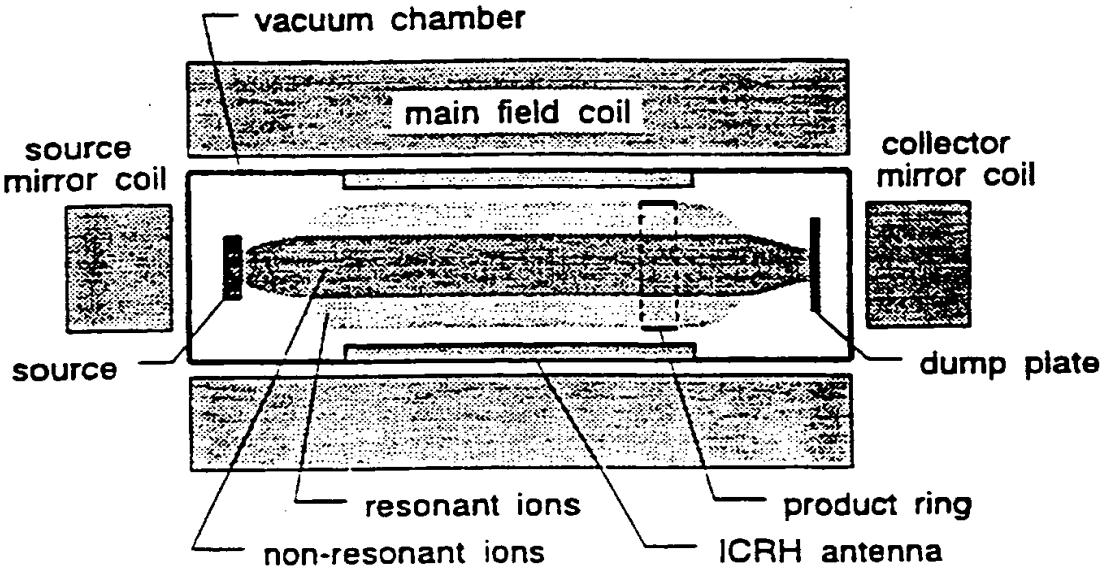
vacuum chamber
main field coil
source mirror coil
collector mirror coil
source
dump plate
resonant ions
product ring
non-resonant ions
ICRH antenna

Fig. 2.2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/19468

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :B01D 59/44; H01J 49/00
US CL : 250/298
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 250/298, 281,290,291

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,081,677 A (DAWSON) 28 MARCH 1978; SEE COL. 13, LINES 9-11; COL. 7, LINES 46-51; COL. 8, LINES 24-29 ; COL. 14, LINES 38-46; AND FIG. 8.	1-2
Y	US 4,757,203 A (GIL ET. AL.) 12 JULY 1988, SEE COL. 5, LINES 45-49.	1-2
Y	US 3,940,615 A (KANTROWITZ) 24 FEBRUARY 1976, NOTE OTHER RING-LIKE COLLECTORS 112 FOR RADICAL COLLECTION.	1-2

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 04 FEBRUARY 1997	Date of mailing of the international search report 05 MAR 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer BRUCE C. ANDERSON Telephone No. (703) 308-4851

Form PCT/ISA/210 (second sheet)(July 1992)*